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Verification and Validation of the Satellite Marine-layer/Elevated Duct Height (SMDH) Technique

by

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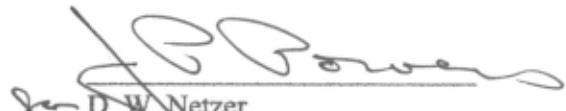

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13. ABSTRACT (Maximum 200 words.) This report is the verification and validation of the Satellite Marine-layer/Evaporation Duct Height (SMDH) technique under development by NAWC Point Mugu, California. The technique provides an estimate of the cloud-top height of stratocumulus clouds in the marine boundary layer for the area viewed by a polar orbiting weather satellite. The top of the marine boundary layer is the optimum coupling height for elevated ducts. Knowledge of the elevated duct height over the tactical battlespace is quite important. The SMDH technique is one component of a potential shipboard operational system to provide estimates of elevated duct height. The SMDH technique is verified using NOAA AVHRR satellite data and coincident rawinsonde or aircraft measurements from the 1987 FIRE and 1994 MAST data sets. The SMDH technique, which uses an empirical relationship to relate the satellite cloud-top temperature, sea-surface temperature and cloud-top height, is quite useful. There are advantages to using a physically-based model, rather than an empirical equation, to estimate cloud-top height. Some of these advantages are demonstrated using the Naval Postgraduate School's physically-based model with the FIRE and MAST data sets. Conclusions/recommendations include (1) the automation of a cloud-top estimation technique is achievable and development should continue, (2) use a physically-based model, rather than an empirical equation, as the core component of the cloud-top height estimation process.				
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1. Introduction

The evaluation of the NAWC Point Mugu Satellite Marine-layer/Elevated Duct Height (SMDH) technique (also called IR-Duct) has been conducted using *in situ* rawinsonde, sea-surface temperature (SST) and polar orbiter AVHRR data from the Summer 1994 Monterey Area Ship Track (MAST) experiment and the 1987 FIRE marine stratocumulus experiment.

Although the SMDH procedure includes elements for automation of the technique, automation of the SMDH technique was not possible for this study. Automation contains uncertainties such as cloud screening, analysis in broken cloud regions, and sea-surface temperature accuracy. Research issues associated with the automation process are discussed later in this report.

The emphasis of this report is on the evaluation of the empirical equation that relates the cloud-top height with the temperature difference between the cloud top and sea surface. The most accurate evaluation of the empirical equation occurs when a trained meteorologist manually screens the satellite image, selects the cloud-top temperature, computes and applies the correction factor, and uses the equation. To exclude the uncertainties of the automation process from this evaluation, the SMDH technique was performed manually. The manual analysis procedure was designed to replicate the automated process as best as possible.

In the marine boundary layer, the top of the stratocumulus cloud deck occurs at the base of the inversion. This is also the location of the Optimum Coupling Height (OCH) for elevated ducts. Therefore, the terms cloud-top height, marine boundary layer (MABL) depth, stratocumulus-topped boundary layer (STBL) depth, OCH, MABL top, and base of the inversion all refer to the same height in this report.

2. Theoretical Background

In a well-mixed STBL, without cloud decoupling and with only a small air-sea temperature difference, the observed temperature difference, ΔT , between the cloud top and sea surface, and the cloud-top height, Z_{CloudTop} , can be used to estimate the overall STBL lapse rate, $\Gamma = \Delta T / Z_{\text{CloudTop}}$. If the boundary layer is well-mixed but cloud-free, the temperature difference divided by the boundary layer depth would approximate the dry adiabatic lapse rate. If clouds filled the entire depth of the boundary layer, the overall STBL lapse rate would approximate the moist adiabatic lapse rate. In most STBLs, clouds do not fill the entire depth, so there is cloud-free air below the clouds. It is expected that the observed $\Delta T / Z_{\text{CloudTop}}$ lapse rate would be between the dry and moist lapse rates.

Studies have indicated a relationship between the temperature gradient, ΔT , and the boundary layer depth, Z_{CloudTop} . Larger ΔT is correlated with deeper boundary layers. The MAST rawinsonde and FIRE aircraft sounding data sets used in this evaluation reflects this relationship, as seen in Figure 1. **The correlation between ΔT and MABL depth is 0.93 for the 24 combined MAST and FIRE cases.**

In Figure 1, the temperature difference between rawinsonde/aircraft measured temperature at the MABL top and sea-surface temperature is plotted versus the rawinsonde/aircraft measured MABL depth. The dry and moist lapse rates are plotted for comparison. As expected, most data points fall between the dry and moist lapse rates. For five of the 15 MAST cases, the air temperature measured at 3 meters is used in place of measured SST and this adds uncertainty to the temperature difference. Three of the five MAST data points to the right of the moist adiabat lapse rate line use rawinsonde air temperature rather than SST. The other two points are in an upwelling zone where the air temperature is warmer than the SST. The two MAST data points to the left of the dry adiabat are cases with the SST substantially warmer than the air temperature. In the combined MAST and FIRE data set, large air-sea temperature differences or unavailable SST account for the estimated $\Delta T/Z_{\text{CloudTop}}$ lapse rate outside the range of moist to dry adiabatic lapse rate.

The STBL will be adiabatic only under certain conditions (e.g. sufficient turbulence for a well-mixed boundary layer and low surface heating by solar radiation). The STBL meets these two conditions most of the time and an adiabatic or moist adiabatic lapse rate assumption is valid (McBride, 2000). The dry adiabatic lapse rate, approximately -9.8C/km , is the rate at which the air temperature decreases with height for an unsaturated air parcel. The moist adiabatic lapse rate is the air temperature decrease with height for a saturated parcel. This lapse rate is nonlinear, but since the STBL rarely exceeds 1.5 km in height, a constant value of -6.5 C/km is typically used.

An STBL forms in response to the interaction between the cool air near the sea surface and warm, subsiding air aloft. The resulting turbulent mixing generates a steady-state, well-mixed STBL with a small air-sea temperature difference. When these conditions are met, the cloud-top and SST temperature difference, ΔT , and cloud-top height are well correlated. Once the STBL is formed, other meteorological and oceanographic processes can occur which make the measured ΔT slightly less correlated with cloud-top height. Upwelling of cold water or advection of warm air over cooler water increases the air-sea temperature difference, but the temperature difference may not immediately affect the depth of the boundary layer. Advection of air into the boundary layer and cloud entrainment can change the lapse rate in portions of the STBL. Cloud decoupling can occur in the boundary layer. In these cases, the effective lapse rate within the STBL may not be estimated accurately by $\Delta T/Z_{\text{CloudTop}}$.

From Figure 1 it is evident that for a given ΔT , the MABL depth is lower using the dry lapse rate (cloud free) than for a completely cloudy MABL (moist lapse rate). It is expected that the effective $\Delta T/Z_{\text{CloudTop}}$ lapse rate for a cloud-top height estimation technique would be between the dry and moist lapse rates.

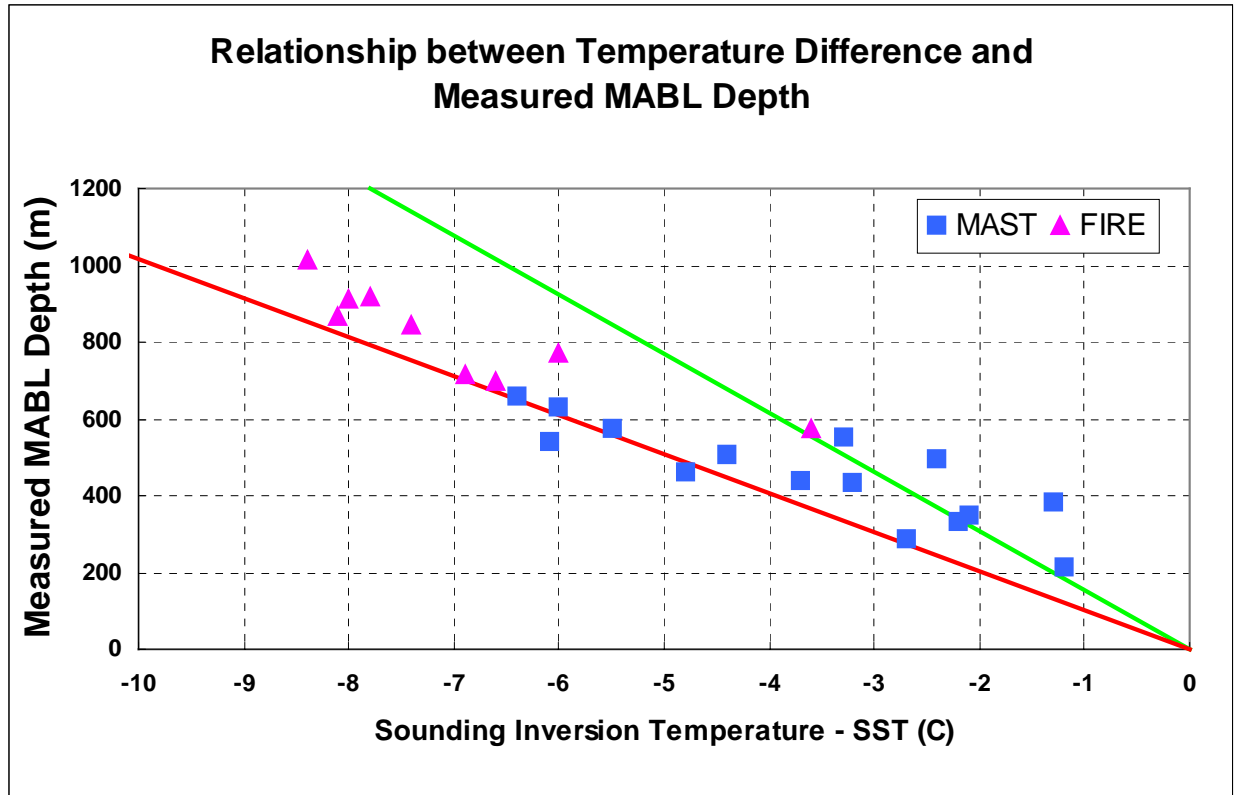


Figure 1. MAST rawinsonde and FIRE aircraft sounding data demonstrates the relationship between ΔT and MABL depth. The temperature difference between rawinsonde or aircraft sounding temperature at the base of the inversion and sea-surface temperature (SST) is plotted versus the rawinsonde or aircraft measured MABL depth. The dry (red) and moist (green) adiabatic lapse rates are plotted for comparison. Three of the five MAST data points to the right of the moist adiabatic lapse rate line use rawinsonde air temperature, measured at 3m, rather than SST. The remaining two points are cases where air temperature is warmer than the SST in an upwelling zone, which decreases the measured ΔT . The two MAST data points to the left of the dry adiabat are cases with the SST substantially warmer than the air temperature.

3. SMDH Technique

The SMDH technique is described in a seven-page facsimile (Helvey, 2000) and further clarified in personal correspondence (Helvey and Eddington, 2000). The SMDH technique has been improved from earlier techniques in the 1980s. Lyons found seasonal relationships between ΔT and cloud-top height using GOES geostationary imagery and 1981-83 soundings from Point Mugu and San Nicolas Island, California. Results are described in NAWC Point Mugu Technical Note 98 (Lyons, 1985a) and Technical Note 100 (Lyons, 1985b). Szymer and Fox (1989) applied this technique to 25 cases from 1986-88 using GOES imagery. The stated accuracy of the technique is ± 400 feet (121.9 m) in 50-80% of the cases (Helvey, 2000). The differences between empirical height-temperature equations for each season were significant, and possibly unrealistic, and the applicability of these equations outside of the southern California region was not known. Consequently, the seasonal empirical equations were abandoned (Helvey and Eddington, 2000).

Empirical Equation

To estimate stratocumulus cloud-top height using the cloud-top and sea-surface temperature difference, the SMDH technique uses an empirical equation based on rawinsonde measurements, without any assumptions about the effective lapse rate of the boundary layer. The equation is an interim replacement for the seasonal equations, pending the outcome of further research (Helvey and Eddington, 2000). The SMDH empirical relation between cloud-top height and temperature difference was derived using a best-fit curve based on some UCLA 1949-52 research cruise data from the eastern Pacific (Helvey, 2000). The UCLA data did not include sea-surface temperature, so monthly sea-surface temperature climatology was used (Helvey and Eddington, 2000). The relation is:

$$\Delta T = T_{\text{CloudTop}} - T_{\text{SeaSurface}} \quad (1)$$

$$Z_{\text{CloudTop}} = -75.43 * \Delta T + 2.105 * (\Delta T)^2 \quad (2)$$

with units ΔT in Celsius and Z_{CloudTop} in meters. The technique is applied only if $\Delta T < 0$. In future automated processing, when $\Delta T > 0$ and low overcast or fog exist, a nominal cloud-top height (50-100 m) would be assigned (Helvey and Eddington, 2000).

The characteristics of Equation 2 are evident in Figure 2. Cloud-top height was computed using Equation 2 for ΔT values between zero and -15.0 C. For reference, the dry and moist adiabatic lapse rates are plotted. The lapse rate for the empirical equation is less than the dry lapse rate. This means that for a given ΔT , below 1200 m the equation estimates a lower boundary layer depth than for a cloud-free MABL (dry lapse rate). For $\Delta T = -4.0$ C, the equation estimates the cloud-top height at 335.4 m, while estimates using the dry and moist lapse rates are 410 m and 620 m, respectively. To generate a depth of 410 m using Equation 2, ΔT must be -4.8 C; similarly -6.9 C equates to a 620 m depth. **Even with perfect input data (100% accurate and no air-sea temperature difference), Equation 2 should generate lower cloud-top heights than measured.**

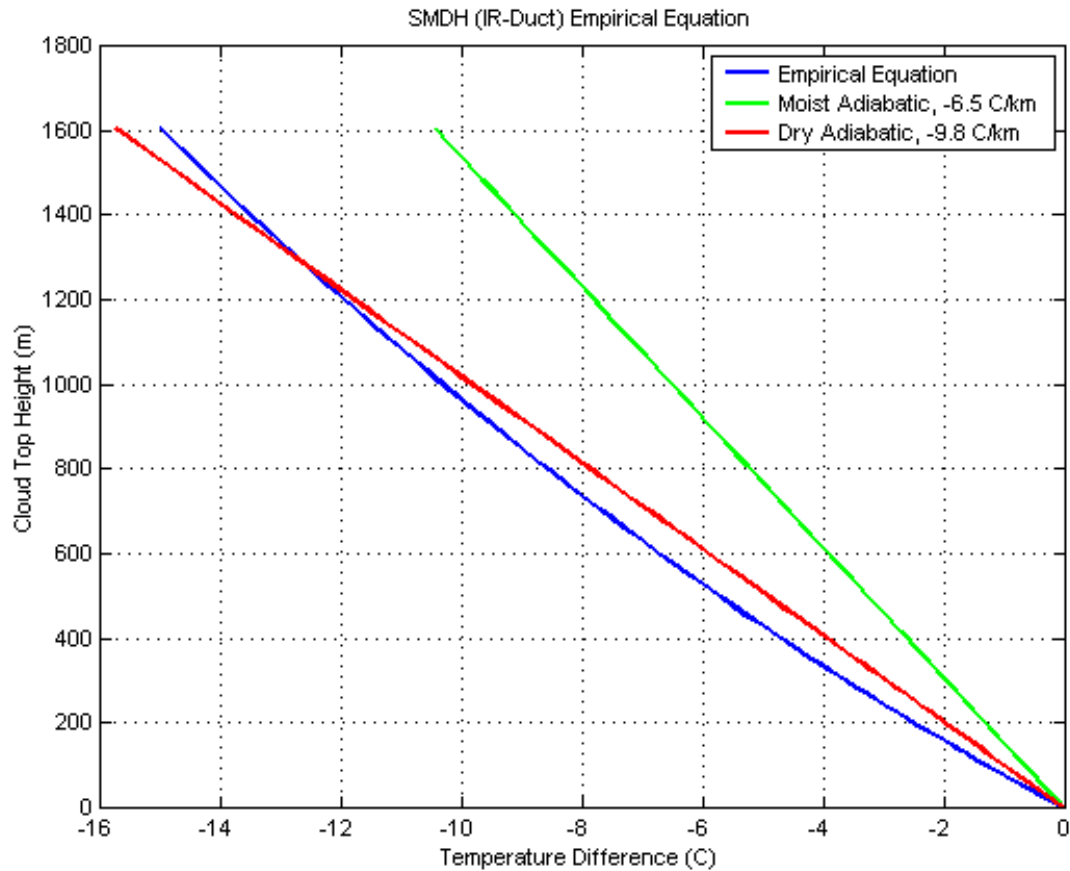


Figure 2. Cloud-top height (m) was estimated using Equation 2 using theoretical temperature difference values from zero to -15.0 C. The output from Equation 2 is plotted in blue. The dry (red) and moist (green) adiabatic lapse rates are plotted for reference. The lapse rate for the empirical equation is less than the dry lapse rate. This means that for a given ΔT , below 1200 m the equation estimates a lower boundary layer depth than for a cloud-free MABL (dry lapse rate).

Manual Analysis Procedure

The manual analysis procedure used in this study is described below. The NAVO sea-surface temperature gridded analysis fields were not available for this study. Instead SST fields computed from AVHRR satellite images were used to compute the "temperature correction factor" prescribed by Helvey (2000).

Step 1: Determine cloud-top temperature from AVHRR Channel 4.

- Use TeraScan Box Statistics function to obtain the range of values and statistics for 3x3 pixel, 5x5 pixel, and 7x7 pixel boxes centered on the rawinsonde location.
- If the box areas are partly cloudy or clear, the nearest area with overcast stratus will be used.

- From the box statistics, choose a representative value for T_{CloudTop} and a range of T_{CloudTop} values.

Step 2: Determine ocean surface temperature from AVHRR Channel 4.

- In a nearby clear area(s), use 3x3, 5x5, 7x7 boxes to determine Channel 4 ocean temperature.

Step 3: Determine the sea-surface temperature in the clear region at the exact locations used in Step 2.

- Option 1: use AVHRR SST field for that satellite image
- Option 2: use previous AVHRR SST field

Step 4: Compute the "upper-level atmospheric attenuation" correction factor, $\Delta T_{\text{Correction}}$, which is the difference between the SST and Channel 4 surface temperature in the clear region.

$$\Delta T_{\text{Correction}} = \text{SST}_{\text{ClearArea}} - T_{\text{Ch4Surface}}$$

Step 5: Add the "upper-level atmospheric attenuation" correction factor (Step 4) to the AVHRR Channel 4 cloud-top temperature (Step 1).

$$T_{\text{CorrectedCloudTop}} = T_{\text{CloudTop}} + \Delta T_{\text{Correction}}$$

Step 6: Determine the sea-surface temperature at the ship location (rawinsonde launch site).

- Option 1: use ship-measured SST
- Option 2: use previous AVHRR SST field
- Option 3: use the 3-meter air temperature measured on the ship; this is the first rawinsonde data level.

Step 7: Compute the temperature difference, ΔT , between the corrected cloud-top temperature and the corresponding SST value.

$$\Delta T = T_{\text{CorrectedCloudTop}} - \text{SST}$$

set *positive* ΔT values to zero.

Step 8: Estimate the Cloud-Top Height using the empirical relationship, Equation 2.

Analysis Note 1: For the 1994 MAST data, the ship-measured SST data is not available for five of the 15 cases and the rawinsonde 3-meter air temperature was used in place of the SST.

Analysis Note 2: For the MAST and FIRE cases, the entire region was cloudy, so the correction factor could not be computed.

Cloud-Top Temperature Correction Factor

Helvey (2000) indicates the correction factor is required for both AVHRR and GOES imagery to compensate for a cold bias caused by moisture or other attenuation above the STBL. In Technical Note 100, using GOES data in the early 1980s Lyons found that "typically cloud top temperature estimates are too cold by one to three degrees. In cloud free regions SST is colder by a nearly identical amount." To compensate, buoy or ship SST measurements were used to compute an SST correction factor and this same correction was applied to warm the cloud-top temperature (Lyons, 1985b). Szymer and Fox (1989) did not find a cold bias using 25 cases of 1986-88 GOES data, so no temperature correction was applied.

For the MAST and FIRE cases, the AVHRR channel 4 cloud-top temperature compared quite favorably with the rawinsonde temperature at the top of the boundary layer, so a correction factor does not appear to be needed. The correction factor warms the cloud-top temperature, which decreases ΔT input to Equation 2 and decreases the estimates of STBL depth. Since the correction factor could not be computed for the MAST and FIRE cases, the SMDH performance statistics are better than if the correction factor had been applied.

4. Data Sets

MAST Data

The purpose of the MAST experiment was to obtain STBL measurements to determine ship track formation and evolution processes. The data set, which has been used for dozens of journal articles, is useful for evaluation of SMDH. NPS thesis student Blake McBride screened the MAST data set for potential cases to be used in his thesis on a physical (not statistical) technique for estimation of cloud-top height, and used 21 MAST cases.

For the purposes of providing the best possible input data for SMDH, six of the cases were excluded for the same reasons listed below:

- Rawinsonde times were more than 90 minutes different than satellite overpass time and unrepresentative of the conditions measured by the satellite.
- AVHRR Channel 4 IR temperature did not match the rawinsonde MABL top temperature within approximately 1.0 C.
- High variability of the Channel 4 temperatures in the vicinity of the rawinsonde, which indicates broken cloud conditions.
- Upper-level clouds are apparent to the analyst in the imagery or from Channel 4 temperatures being significantly colder than the rawinsonde temperature.
- Boundary layer structure is not well-mixed.
- Complicated meteorology.

The SMDH technique was applied to the remaining 15 cases. In these cases, there were no nearby clear areas to compute the cloud-top temperature correction. In ten of the 15 MAST cases, sea-surface temperatures were available and used. For the remaining five cases, the

rawinsonde air temperature, measured at 3 meters, was used in place of the sea-surface temperature.

FIRE Data

The Marine Stratocumulus Intensive Field Observations phase of the First International Satellite Cloud Climatology Project Regional Experiment (FIRE) occurred 29 June - 19 July 1987 off the coast of southern California. This data set has been widely used in journal articles. Nine of the aircraft spiral soundings from this data set have been used in this study. Soundings were chosen based on NOAA-10 AVHRR satellite imagery and SST measurement availability. The time between the satellite imagery and the sounding was allowed to be longer than 90 minutes provided the AVHRR cloud-top temperature and sounding inversion temperature was within 0.5C. The FIRE cases are measurements of deep, well-mixed STBLs, with soundings in locations without broken conditions, and cloud-top temperature and sounding inversion temperature within 0.5C. Upper-level clouds and cloud decoupling are not evident. One case had a five hour time difference between the sounding and the satellite overpass, yet the sounding seemed quite representative of conditions at the later satellite overpass time. SMDH performed quite well for this case. Air temperature measurements at low levels are not available because the aircraft did not fly below about 75 meters. Figure 3 indicates the locations of the MAST and FIRE soundings.

5. Results with MAST and FIRE Cases

For these 24 cases, SMDH cloud-top height estimate underestimated the STBL depth in all cases, with a root mean square (RMS) error of 171.4 m (562 ft). These cases have no cloud-top temperature correction factor applied, which would decrease the ΔT and further reduce the estimated cloud-top height. Figure 4 is a scatterplot of the SMDH cloud-top height estimations compared with the measured height. For comparison, the one-to-one line is included, where SMDH estimate would be to equal the measured heights. Figure 5 is a scatterplot similar to Figure 4, with the linear regression line plotted and regression equation and R^2 value listed. The R^2 value indicates the amount of the data spread represented by the regression line. The regression line has a slope of nearly one, and the bias toward underpredicting the cloud-top height is evident. The correlation coefficient for the regression line, R , is 0.94 and the bias is approximately -167.0 meters.

Figure 6 demonstrates that the temperature difference, using AVHRR cloud-top and sea-surface temperature, is correlated with MABL depth, and the relationship in the rawinsonde/sounding data (Fig. 1) is reflected in the remote sensing data. Figures 1 and 6 look quite similar because the included MAST and FIRE cases have rawinsonde and cloud-top temperatures within 1.0 C and 0.5 C, respectively.

SMDH performed the worst on six cases which lie to the right of the moist adiabat in Figure 6, and had the least error on the three cases lying to the left of the dry adiabat. This is to be expected from the behavior of Equation 2. As shown in Figure 2, the SMDH predicted cloud-top heights are less than those predicted by the dry adiabatic lapse rate. The points in Figure 6

which are to the left of the dry adiabatic have the least height difference. The six cases to the right of the moist adiabat have heights significantly higher than the height generated by using the dry adiabat lapse rate to estimate an effective lapse rate for each case. In fact, using Equation 2, those six cases need an approximately 2.0 C larger temperature difference to generate that large of STBL depth. The three cases to the left of the dry adiabat are cases where the sea-surface temperature is greater than the air temperature by 0.6 C to 1.2 C. These three cases had error less than 45 meters. The excellent performance of SMDH in these cases indicates a possible bias in Equation 2 towards warmer sea-surface temperatures than air temperatures.

Computing the statistics for two experiments separately, SMDH has a 162.8 m RMS difference for the 15 MAST cases and a 185.0 m RMS difference for the nine FIRE cases. The FIRE cases have deeper STBLs and are not in upwelling regions. It is surprising that SMDH performed worse using the more classical STBL cases in the FIRE experiment. However, the three cases with the smallest error (< 45 m) are MAST cases and decrease the overall MAST RMS difference.

The combination of sea-surface and cloud-top temperature uncertainties will affect ΔT . It is possible for the effects to offset. It is also possible the combined effects will significantly increase or decrease ΔT , thereby dramatically affecting the SMDH height estimate. The sea-surface temperature is the most variable, especially in the coastal region. The cases included in this report have the best available data to compute ΔT .

Measured data has inherent uncertainty and examples of possible effects of cloud-top and sea-surface temperature uncertainties are presented in Figures 7 and 8. A 0.5 C error in the cloud-top temperature measurement causes a 38.2 m error, a 1.0 C error in SST causes a 77.5 m error. If the two errors combine to cause a 1.5 C error in ΔT , the SMDH height change is 117.9 meters. These errors are in addition to the errors inherent to Equation 2.

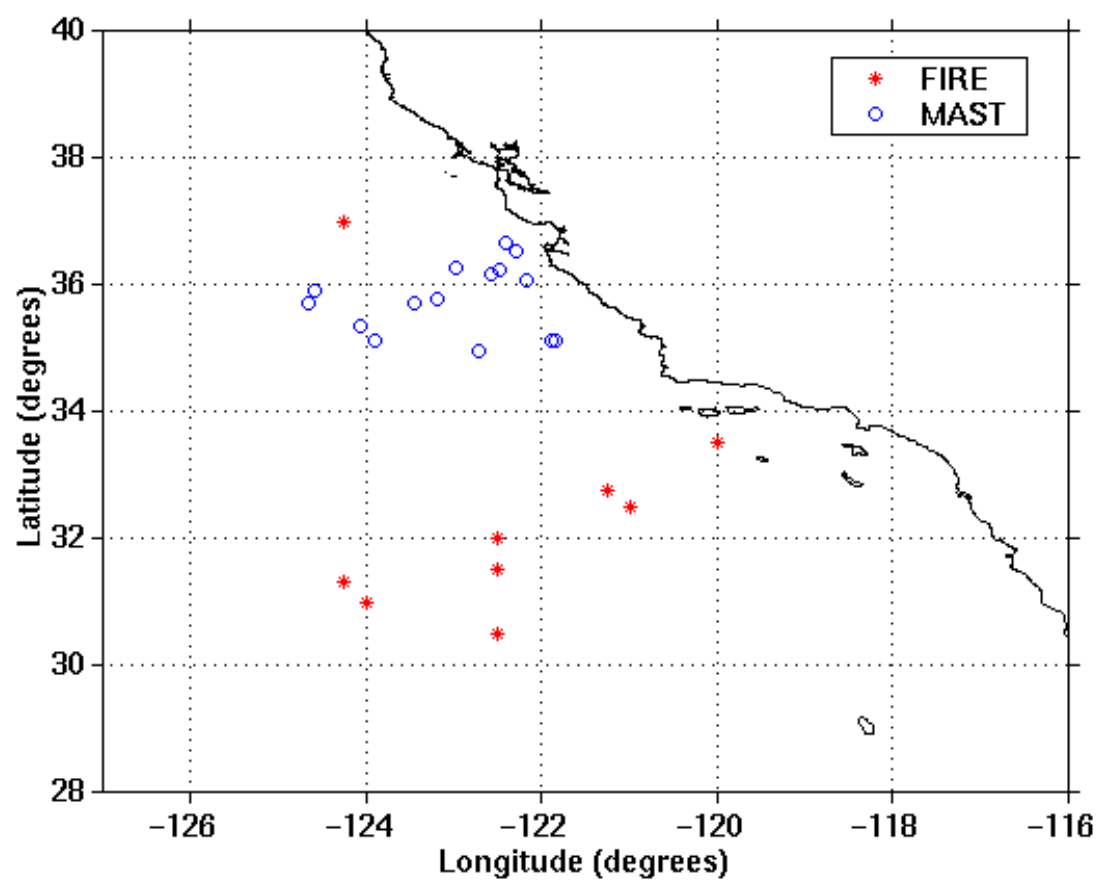


Figure 3. Locations of the MAST (blue) and FIRE (red) soundings used in this study.

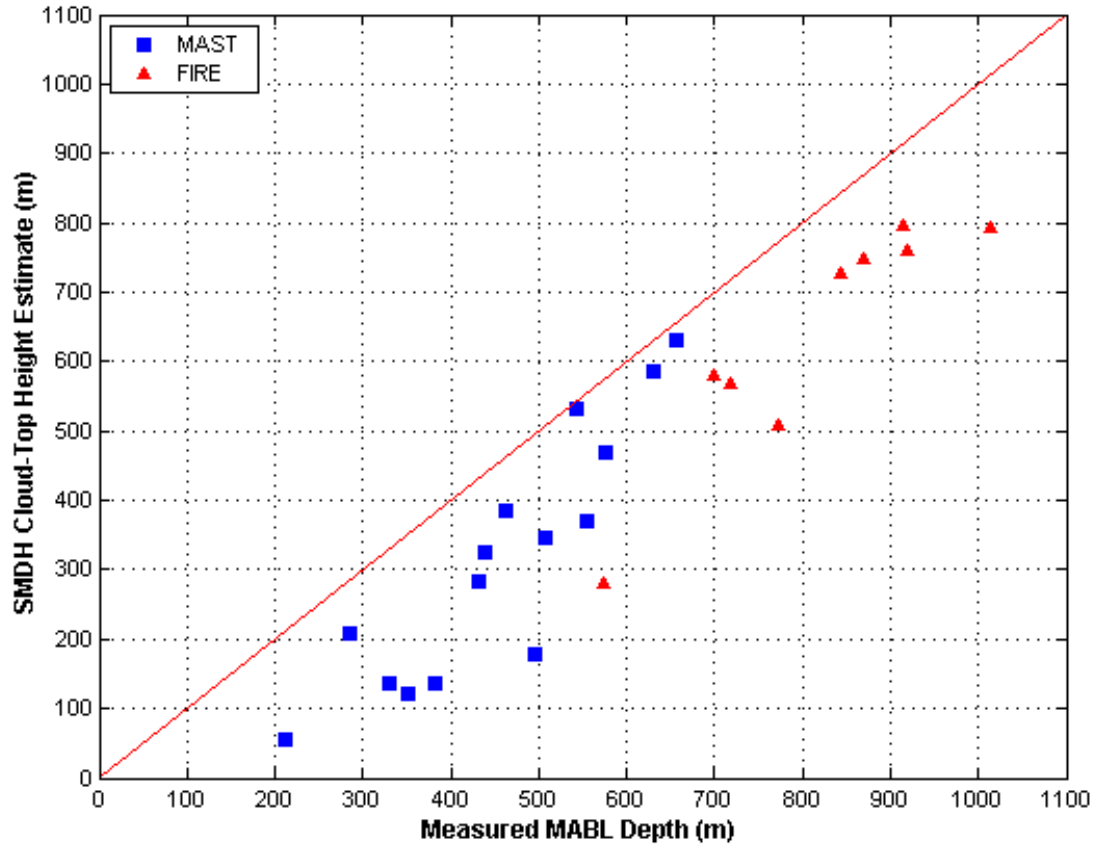


Figure 4. SMDH cloud-top height (m) estimates for the 15 MAST and 9 FIRE cases, without the cloud-top temperature correction applied, are compared with the measured boundary layer depth (m). The one-to-one line (red), indicates where the SMDH estimate would equal the measured MABL depth.

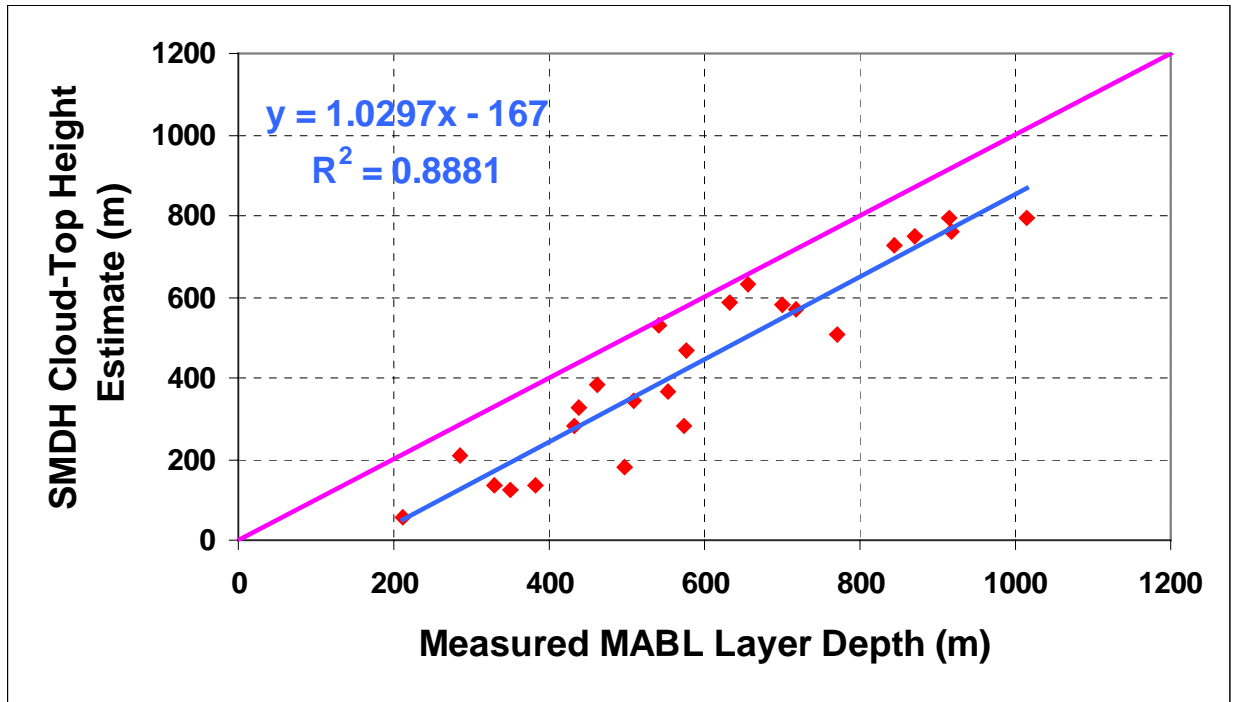


Figure 5. Scatterplot of the SMDH estimate and measured MABL depth (m), similar to Fig. 4, with the linear regression line plotted in blue and regression equation and R^2 value listed in the upper left corner. The magenta line is the one-to-one line, as in Fig. 4. The correlation coefficient, R , is 0.94. There is a bias making the SMDH cloud-top height estimates too low. The slope of the regression line is almost one, which indicates the bias is approximately -167 m.

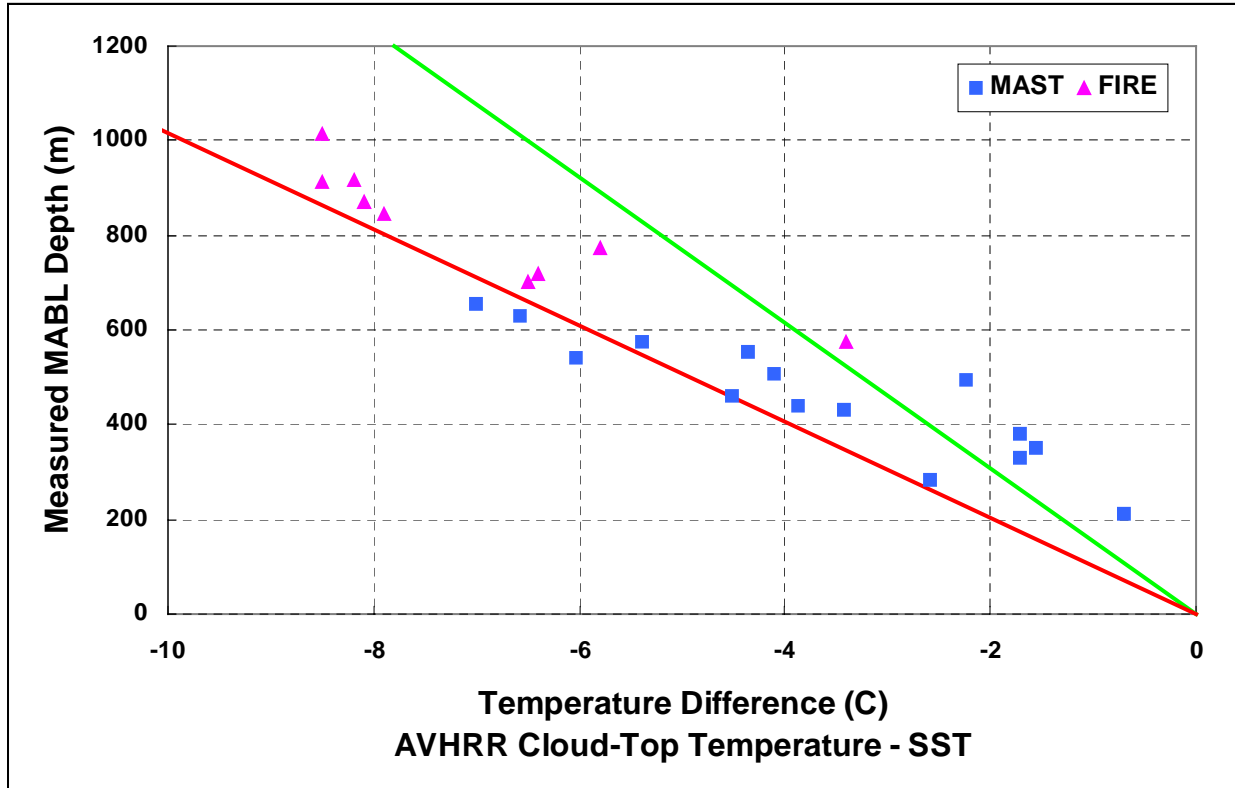


Figure 6. The temperature difference (C) between AVHRR cloud-top temperature (channel 4) and sea-surface temperature is plotted versus measured boundary layer depth. Figure 6 demonstrates that the temperature difference is correlated with MABL depth, and the relationship in the rawinsonde data (Figure 1) is reflected in the remote sensing data. Figures 1 and 6 look quite similar because the included MAST and FIRE cases have sounding and cloud-top temperatures within 1.0 C and 0.5 C, respectively.

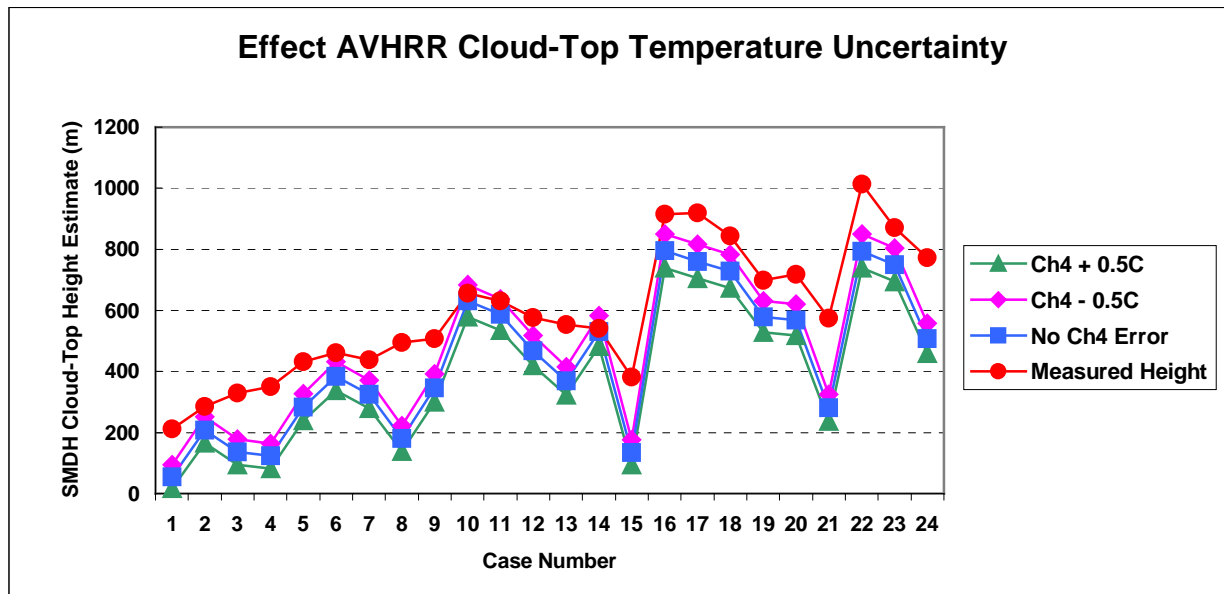


Figure 7. The effect of a ± 0.5 C Channel 4 cloud-top temperature variation on SMDH cloud-top height estimates is presented. The case with no Channel 4 error is the same case presented in Figs. 4-6. The measured MABL height is in red. A 0.5 C cloud-top temperature error causes a 38.2 m change in the SMDH height estimate.

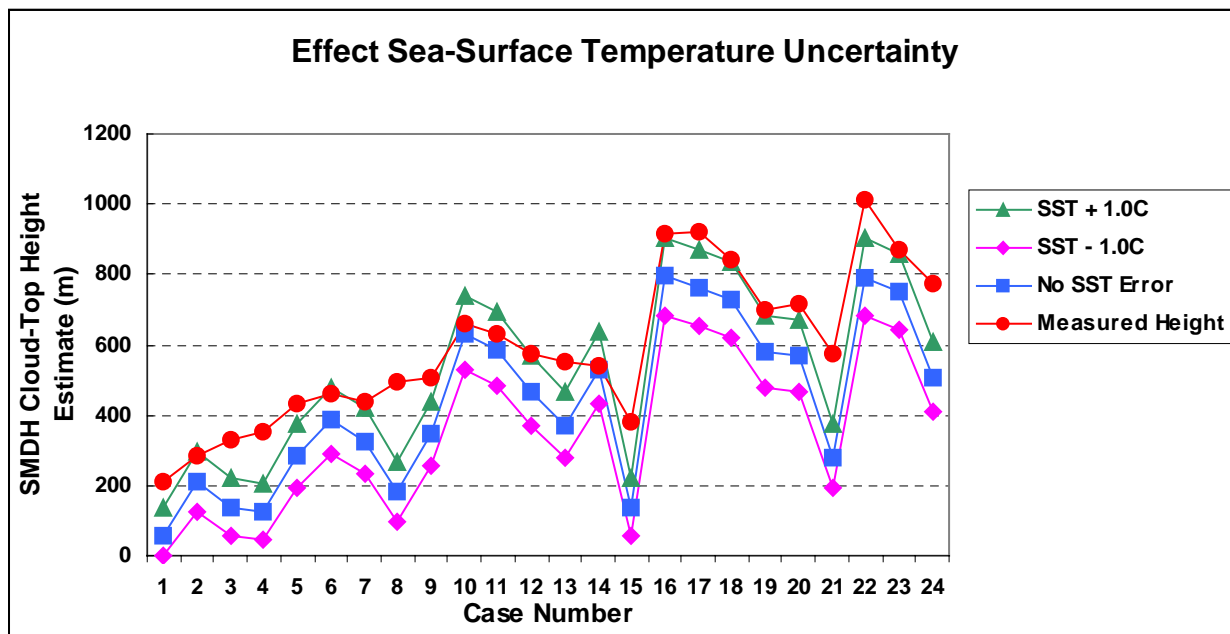


Figure 8. The effect of a ± 1.0 C sea-surface temperature variation on SMDH cloud-top height estimates is presented. The case with no SST error is the same case presented in Figs. 4-6. The measured MABL height is in red. A 1.0 C sea-surface temperature error causes a 77.5 m change in the SMDH height estimate.

6. NPS Physically-Based Model

NPS has designed a physically-based model to estimate cloud-top height from AVHRR or GOES infrared (channel 4) cloud-top measurements. The preliminary work on this method is described in the NPS Masters Thesis of LT Marvin B. McBride (2000). McBride used the MAST data set to derive this technique.

There are significant differences between the SMDH and NPS approaches. Both techniques use SST and cloud-top temperature as input values. The SMDH technique has one unknown: boundary layer depth. The NPS technique has two unknowns: (1) cloud-base height and (2) vertical cloud fraction (percent), which is the vertical fraction of the STBL with clouds. Figure 9 illustrates the NPS technique, which uses estimates of cloud-base height and cloud fraction to compute the boundary layer depth, using the dry adiabatic lapse rate in the cloud-free portion, from the surface to cloud base, and a pseudo-adiabatic lapse rate of -7.0 C/km , in the clouds. The effective lapse rate, $\Gamma = \Delta T / Z_{\text{CloudTop}}$, is denoted by a green line in Figure 9.

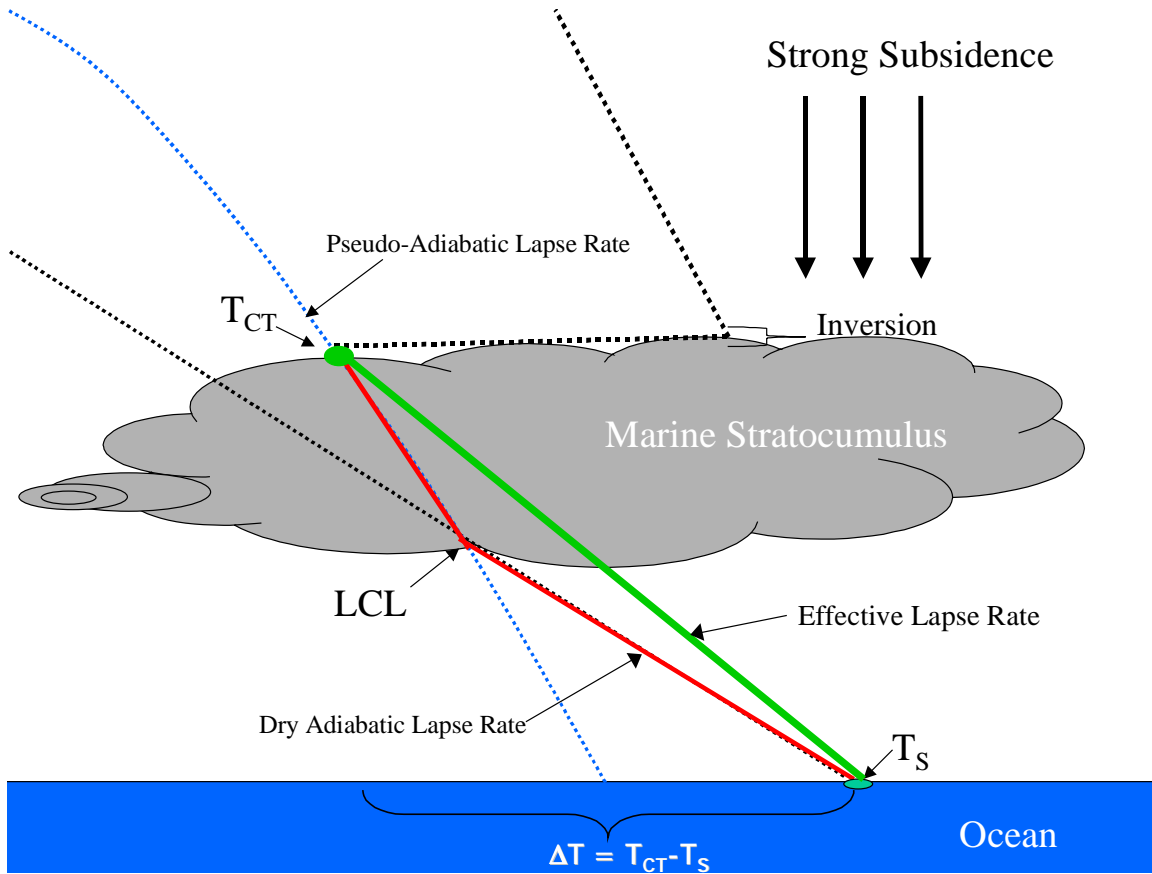


Figure 9. The NPS technique uses as input the sea-surface temperature (T_S) and cloud-top temperature (T_C). The lifted condensation level (LCL) is the base of the cloud. The dry adiabatic lapse rate is used in the cloud-free region and the pseudo-adiabatic lapse rate is used in cloud. The effective lapse rate of the entire STBL (green) is $\Gamma = \Delta T / Z_{\text{CloudTop}}$.

Steps of the NPS Technique

Step 1: Using the measured ΔT and the dry adiabatic lapse rate, estimate the boundary layer depth with no clouds (all temperatures in $^{\circ}\text{C}$, lapse rates in $^{\circ}\text{C}/\text{m}$, heights in meters).

$$Z_{\text{dry}} = \Delta T / \Gamma_{\text{dry}} \quad (3)$$

Step 2: Assuming a vertical cloud fraction of 1/3 (meaning 2/3 cloud-free), estimate the height of the cloud base for a 2/3 cloud-free boundary layer.

$$Z_{\text{CloudBase}} = 2/3 * Z_{\text{dry}} \quad (4)$$

Step 3: Using the dry adiabatic lapse rate, Γ_{dry} , and the sea-surface temperature, T_s , estimate the cloud-base temperature for a 2/3 cloud-free boundary layer.

$$T_{\text{CloudBase}} = \Gamma_{\text{dry}} * Z_{\text{CloudBase}} + T_s \quad (5)$$

Step 4: Using the measured cloud-top temperature, T_{CT} , the estimated cloud-base temperature, $T_{\text{CloudBase}}$, and the pseudo-adiabatic lapse rate, Γ_{moist} , estimate the cloud depth (m).

$$\text{CloudDepth} = (T_{\text{CT}} - T_{\text{CloudBase}}) * \Gamma_{\text{moist}} \quad (6)$$

Step 5: Compute the cloud-top height, Z_{CloudTop} , using the estimates of cloud-base height and cloud depth.

$$Z_{\text{CloudTop}} = Z_{\text{CloudBase}} + \text{CloudDepth} \quad (7)$$

Step 6: If the cloud-top height is less than 400 meters, recompute the cloud-top height using an assumption of 2/3 vertical cloud fraction (meaning 1/3 cloud-free). Use Equation 4 with a cloud-free ratio of 1/3 vice 2/3. Using the new estimate of cloud-base height, use Equations 5-7 to generate a new, higher estimate of cloud-top height. The rationale for this step is that shallow STBLs typically have a higher vertical cloud fraction. The 400m break point was determined from observation by McBride (2000).

Figure 10 illustrates Steps 1-5. The effect of using the pseudo-adiabatic lapse rate in the cloud is to increase the cloud-top height estimate over the estimate using the dry adiabatic rate. The 1/3 vertical cloud fraction results in a STBL with 41% cloud and 59% cloud free. Figure 11 illustrates Step 6. Using a 2/3 vertical cloud fraction generates a deeper STBL compared with the result using the 1/3 cloud fraction. The 2/3 vertical cloud fraction results in a STBL with 75% cloud and 25% cloud free.

Results from MAST and FIRE

For these 24 cases, the NPS cloud-top height has a root mean square (RMS) error of 95.3 m (312.7 ft). Figure 12 is a scatterplot of the NPS cloud-top height estimations compared with the measured height. For comparison, the one-to-one line, where NPS estimate would be to

equal the measured heights, is included. Notice that the NPS technique does not have a clear over or underestimation bias. Figure 13 is a scatterplot similar to Fig. 12 with the linear regression line plotted and the regression equation and R^2 value are listed. The correlation coefficient for the regression line, R , is 0.94.

Computing the statistics for two experiments separately, the NPS method has a 108.6 m RMS difference for the 15 MAST cases and a 67.3 m RMS difference for the nine FIRE cases. The 1/3 and 2/3 cloud ratios used in this method were based on MAST data with air temperature measured at 3.0 meters used because sea-surface temperature was not available for all cases. Ten of these MAST cases use SST, and the RMS difference is higher than found in McBride (2000). The performance in the FIRE cases, an independent data set for the NPS technique, is excellent. Similar to SMDH, the NPS technique had its worst performance with the six shallow cases.

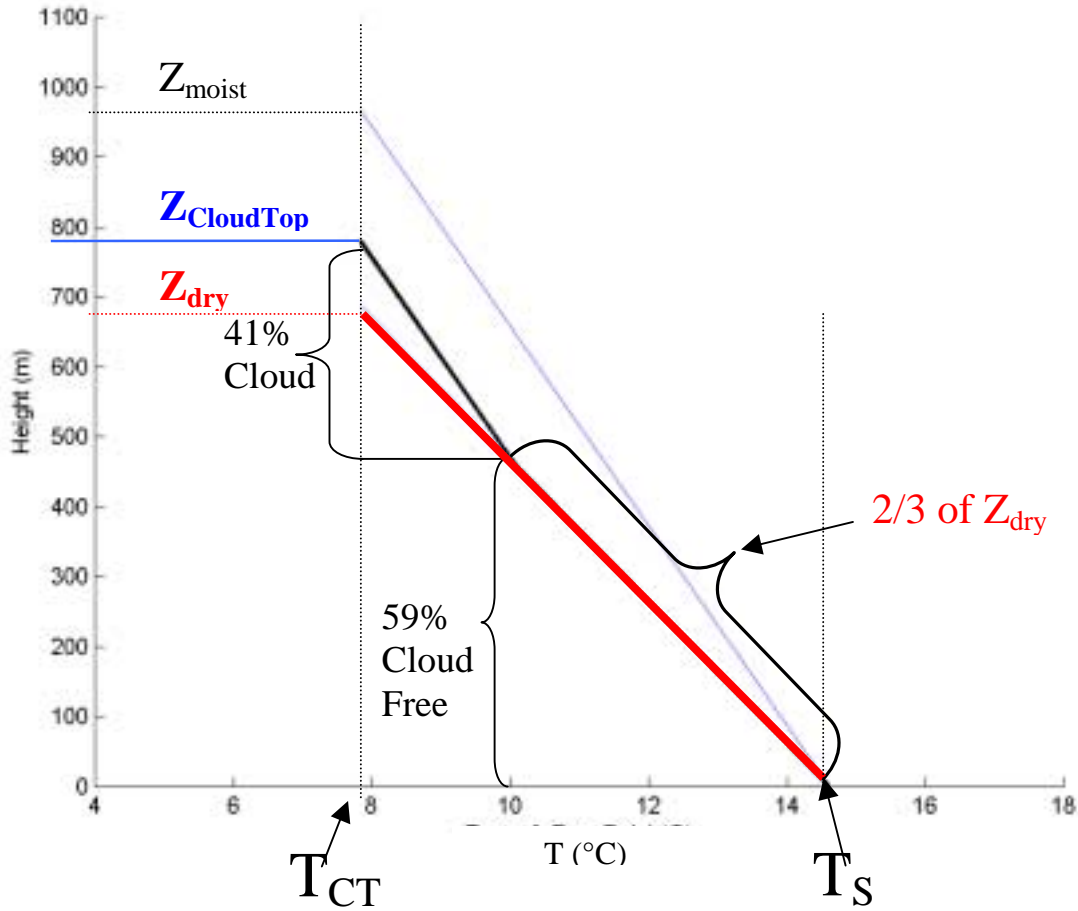


Figure 10. The "1/3 vertical cloud fraction assumption" (meaning 2/3 of STBL is cloud-free) of the NPS technique is illustrated. The input parameters are cloud-top temperature, T_{CT} and sea-surface temperature, T_S . The output parameter is cloud-top height, $Z_{CloudTop}$. The red line represents the dry adiabatic lapse rate applied to the temperature difference ($T_{CT} - T_S$). Z_{dry} is the boundary layer depth assuming no clouds in the boundary layer. Z_{moist} is the boundary layer depth computed using the moist (pseudo-adiabatic) lapse rate, assuming clouds exist throughout the entire STBL. Assuming 2/3 of the STBL is cloud-free, the moist adiabatic lapse rate is used to compute the cloud depth; this is represented by the black line from cloud base to $Z_{CloudTop}$. The estimated cloud-top height, $Z_{CloudTop}$, is between Z_{dry} and Z_{moist} , the heights estimated using the dry and moist lapse rates, respectively. The effective lapse rate of the boundary layer, $\Gamma = \Delta T / Z_{CloudTop}$, is between the dry and moist adiabatic lapse rates.

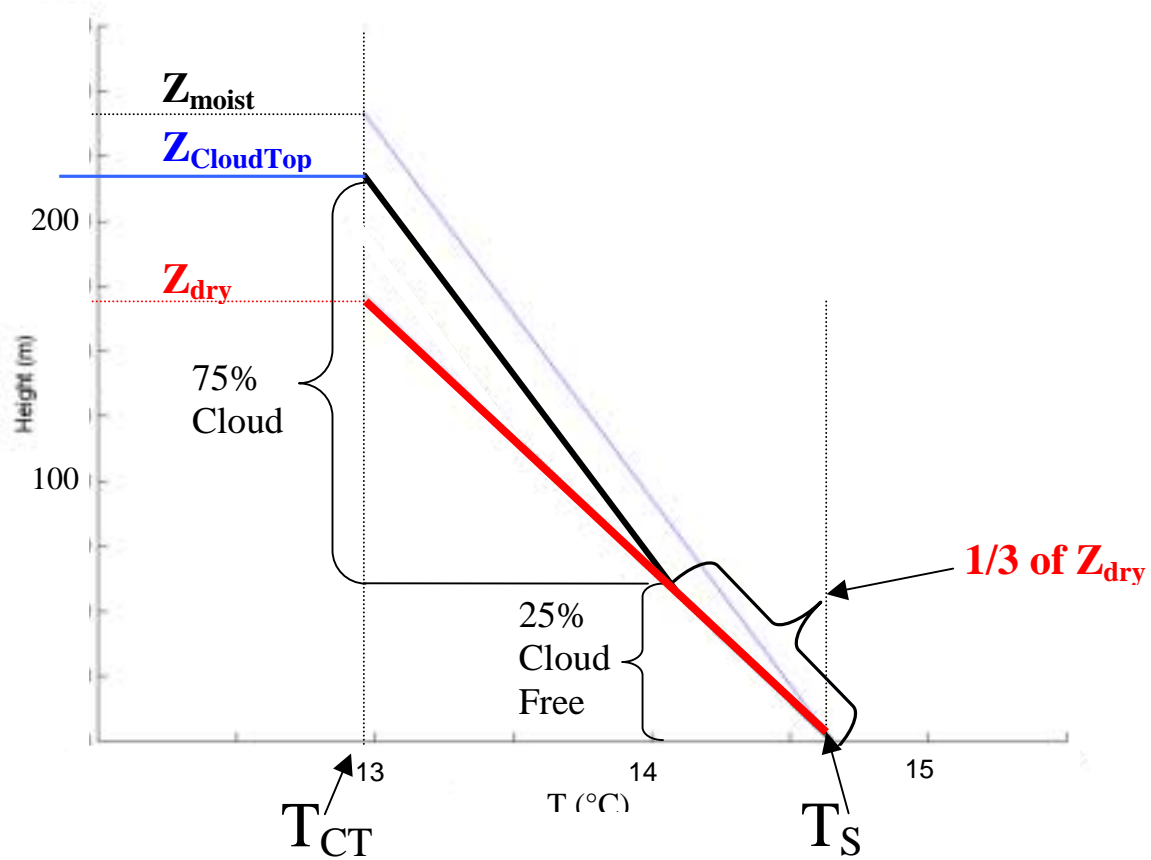


Figure 11. The "2/3 vertical cloud fraction assumption" (meaning 1/3 of STBL is cloud-free) of the NPS technique is illustrated. The input parameters are cloud-top temperature, T_{CT} and sea-surface temperature, T_S . The output parameter is cloud-top height, $Z_{CloudTop}$. The red line represents the dry adiabatic lapse rate applied to the temperature difference ($T_{CT} - T_S$). Z_{dry} is the boundary layer depth assuming no clouds in the boundary layer. Z_{moist} is the boundary layer depth computed using the moist (pseudo-adiabatic) lapse rate, assuming clouds exist throughout the entire STBL. Assuming 1/3 of the STBL is cloud-free, the moist adiabatic lapse rate is used to compute the cloud depth; this is represented by the black line from cloud base to $Z_{CloudTop}$. The estimated cloud-top height, $Z_{CloudTop}$, is between Z_{dry} and Z_{moist} , the heights estimated using the dry and moist lapse rates, respectively. The effective lapse rate of the boundary layer, $\Gamma = \Delta T / Z_{CloudTop}$, is between the dry and moist adiabatic lapse rates.

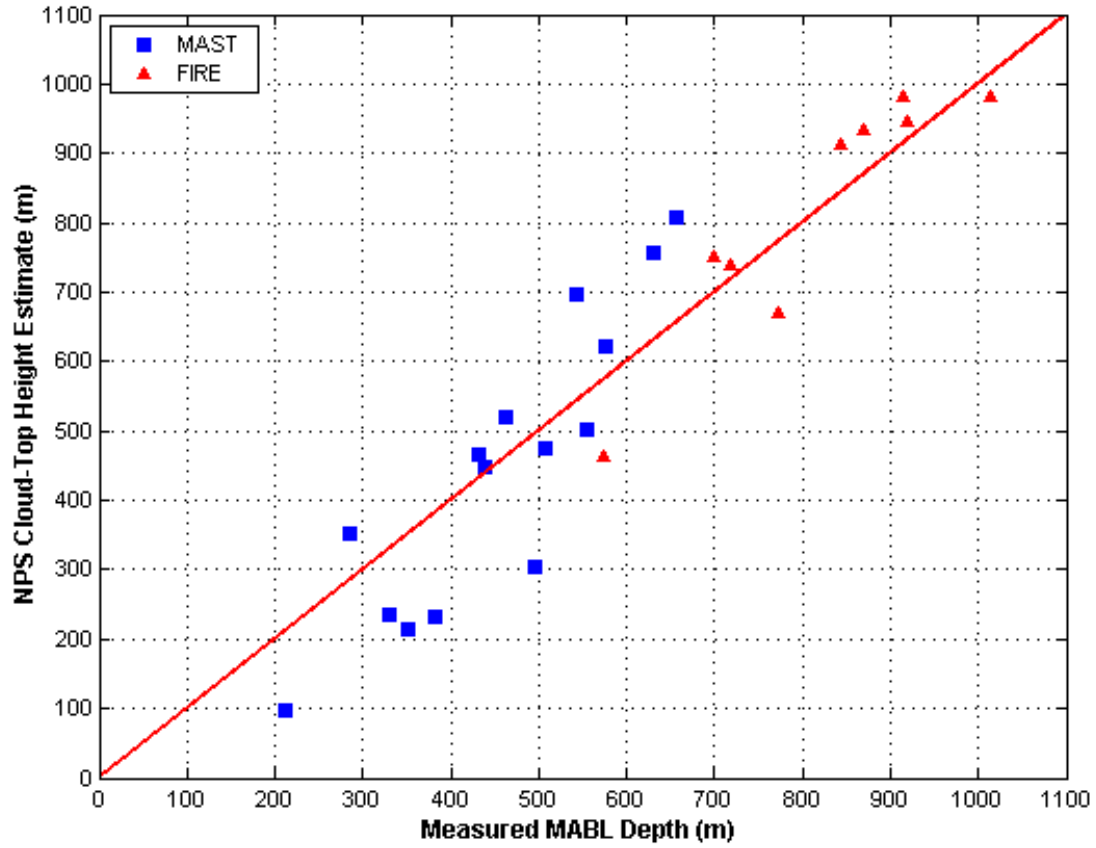


Figure 12. NPS cloud-top height (m) estimate for the 15 MAST and 9 FIRE cases are compared with the measured boundary layer depth (m). The one-to-one line (red), indicates where the NPS estimate would equal the measured MABL depth.

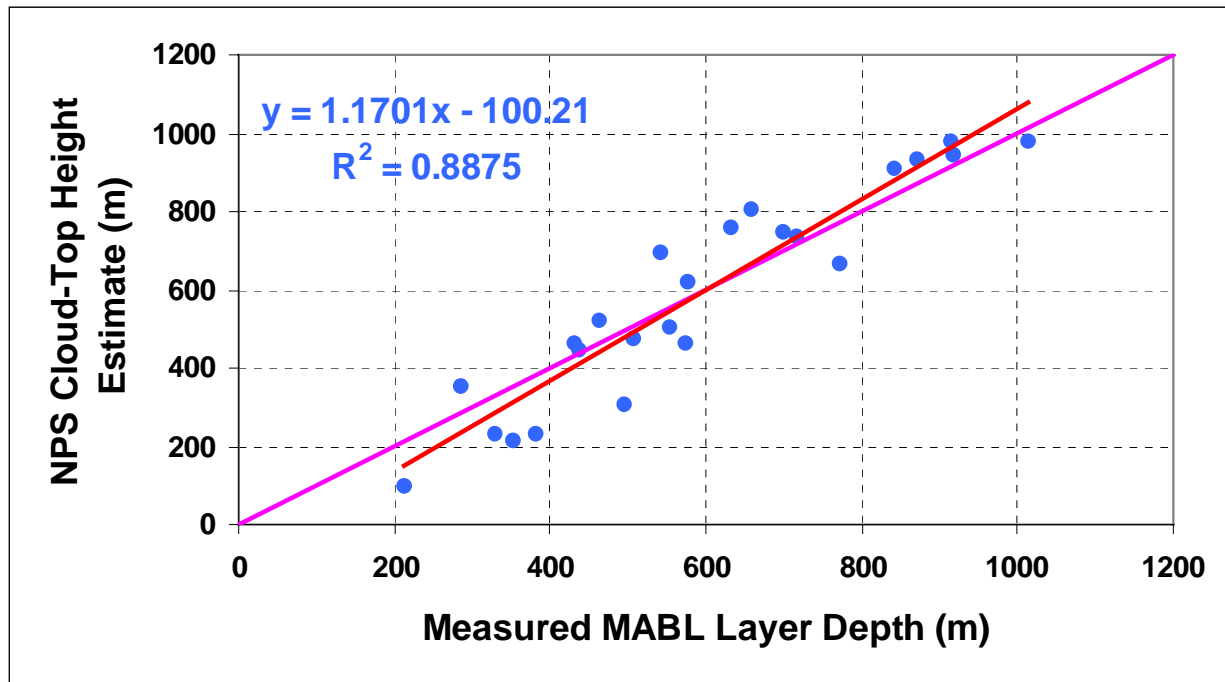


Figure 13. Scatterplot of the NPS estimate and measured MABL depth (m), similar to Fig. 12, with the linear regression line plotted in red and the regression equation and R^2 value listed in the upper left corner. The magenta line is the one-to-one line, as in Fig. 12. The correlation coefficient, R , is 0.94.

7. Comparison of SMDH and NPS Methods

Comparing the SMDH and NPS methods for the 24 cases, the RMS difference for the physically-based NPS model (95.3 m) is significantly better than the SMDH results (171.4 m). The performance of the physical-based model for the FIRE cases is substantially better than for the MAST cases, while SMDH has higher RMS difference for the FIRE cases. This is important because the FIRE cases are the more classic STBL conditions away from upwelling regions. The RMS differences for the two methods are summarized in Table 1.

Table 1. Comparison of RMS differences (m) for the SMDH and NPS techniques.

	SMDH RMS Difference (m)	NPS RMS Difference (m)
Combined MAST and FIRE (24 cases)	171.4	95.3
MAST only (15 cases)	162.8	108.6
FIRE only (9 cases)	185.0	67.3

A key difference between the SMDH and NPS methods is that the assumptions in the NPS technique are physically based and can be easily accessed and changed. There is a statistical component to the NPS technique -- the vertical cloud amount ratios were chosen based on least squared error of McBride's MAST data set. As additional sounding, SST and satellite imagery data sets from different ocean basins are evaluated, the cloud fraction assumptions can be refined. In addition, as research increases the overall understanding of STBL structure (e.g. shallow STBLs), the physical model components can be modified.

8. Shallow STBL Cases

Cases with shallow STBL can be difficult to predict. Shallow STBLs have small ΔT values (e.g. 300 m STBL may have ΔT of 2.5-3.0 C). Cloud-top temperature and SST measurement errors (e.g. 0.5-1.0 C), if they occur, may be a large percentage of a small ΔT value. SMDH has an additional problem in shallow STBL cases due to the properties of Equation 2. Shallow STBLs generally have a high percentage of the entire boundary layer depth in cloud and a significant percentage of the lapse rate is moist adiabatic. Since the cloud-top height predicted by Equation 2 is less than the height predicted by the dry adiabatic lapse rate, shallow STBL cases are significantly underpredicted. Shallow cases in regions of upwelling may pose additional problems. If upwelling occurs after a steady-state, well-mixed STBL (with no air-sea temperature difference) is formed, then the cooler water will reduce ΔT and SMDH will predict lower cloud-top heights. Similarly, if warm air is advected over cooler water the air-sea temperature will increase resulting in a reduction in ΔT and the estimate of cloud-top height.

In Figure 6, there are six cases where the ΔT versus measured height points are to the right of the moist adiabat. Three are MAST cases which have no SST and air temperature is used; two MAST cases have very cold SSTs (12.2 C and 12.7 C) and the air temperature at 3 meters is 0.8 C warmer than the SSTs. The one FIRE case is in a region of upwelling (SST is 14.4 C) and the aircraft sounding and SST measurement are 3.5 hours after the satellite pass. **While it is reasonable to expect SMDH and other techniques to perform adequately on cases such as these, to demonstrate a point, these six cases are excluded and statistic analysis performed on the remaining 18 cases.**

With the six shallow cases removed, the SMDH RMS difference is 138.3 m, compared with 171.4 m for all 24 cases. The difference for each of the two experiments was computed after excluding the six cases. For the remaining 10 MAST and 8 FIRE cases, SMDH RMS difference was 110.6 m and 166.5 m, respectively. The NPS RMS difference for the 18 cases is 76.8 m, and 88.1 m and 59.8 m for the MAST and FIRE cases, respectively.

Comparing the SMDH and NPS methods, **the NPS model performance including all 24 cases (95.3 m) is better than the SMDH results using only the "best" 18 cases (138.3 m).** The RMS differences for the two methods are summarized in Table 2.

These shallow cases may have some error in ΔT to account for the points being to the right of the moist adiabat, but these are reasonable cases which any cloud-top height estimation technique must be able to adequately predict. RMS difference in these six cases is significantly higher for SMDH than for the NPS technique (245.4 m and 136.4 m, respectively). Both methods need improvement in shallow cases, but only the physically-based NPS model allows for modification of assumptions within the technique.

Table 2. Comparison of RMS differences (m), excluding six cases, for the SMDH and NPS techniques.

	SMDH RMS Difference (m)	NPS RMS Difference (m)
Combined MAST and FIRE (24 cases)	171.4	95.3
Combined MAST and FIRE, excluding six shallow cases (18 cases)	138.3	76.8
MAST only (10 cases)	110.6	88.1
FIRE only (8 cases)	166.5	59.8
Combined six shallow cases	245.4	136.4

9. Automation Process

NPS has demonstrated the capability to automate Mc Bride's technique using TeraScan. The mechanics of automation of SMDH are not too difficult, but the process must be refined and tested. There are automation issues which need further research:

- Incorporate a cloud analysis algorithm that can identify broken clouds decks. As an example, techniques that use the spatial variability of the visible and infrared radiance within a scene are able to produce reliable estimates of SST (low variability and high temperature) and cloud-top temperature (low variability and low temperature).
- Determine if a cloud-top temperature correction technique is needed due to absorption by water vapor above cloud top. Various techniques that use water vapor absorption bands in the IR and microwave will provide this correction.
- Obtain the highest resolution SST analysis or forecast gridded fields and match the SST grid to the resolution of the AVHRR or GOES imagery.
- Incorporate error bounds in the results due to uncertainties in the observations.

10. Conclusions

SMDH Method

- There is a high correlation between ΔT and cloud-top height in the satellite data and in the SMDH results, 0.93 and 0.94, respectively. **This confirms that the useful information in the satellite data can be converted to useful cloud-top height estimates.**
- The behavior of Equation 2, as demonstration in Figure 2, does not describe typical maritime conditions. While there may be meteorological cases observed in nature where the lapse rate throughout the boundary layer is superadiabatic, this is not the typical case. This bias in SMDH is probably due to using monthly SST climatology with the UCLA rawinsonde data. The result is SMDH underpredicts cloud-top height.
- If a statistical technique such as SMDH is used, care must be taken to insure measurement errors or observational biases are removed. Statistical regression techniques require correlation studies under the conditions that control the relationship between the measurements and the estimated parameters (i.e. measurements of cloud-top IR radiance and SST and estimates of cloud-top height). This calls for a research quality data set with spatially and temporally correlated rawinsondes, SST measurements, and satellite imagery in regions of the world where the techniques will be employed .
- Variability in the statistical regression and uncertainties in cloud-top estimates and SST observations define the minimum detectable cloud-top height. This minimum must be identified and reported with all results.
- The need for cloud-top temperature corrections must be discussed further. SMDH should not need a cloud-top temperature correction in the subtropics using properly calibrated satellite data. Under some meteorological conditions, accounting for upper-level moisture may be necessary. The cold bias found in early 1980s GOES imagery is not indicative of current GOES and AVHRR sensor accuracy.

NPS Method

- There is a high correlation, 0.94, between measured and NPS-estimated cloud-top height.
- The NPS model has significantly lower RMS differences than SMDH.
- Further research is needed to refine the assumptions in the NPS model.
- Performance in shallow STBL cases must be improved.

Automation Process

- Automation of a cloud-top height estimation technique is achievable.
- There are portions of the process that require further research to achieve a stand-alone product for Navy ships and METOC regional centers.

11. Recommendations

- The current empirical relationship (Equation 2) should be replaced by a method that includes a physically based model, rather than a purely empirical equation.
- There are significant benefits of a physically-based model:
 - Model assumptions can be modified later, if needed, where a statistical equation cannot.
 - A physically-based model could potentially accept input from outside data sources, such as ship observations or buoys.
 - In addition to providing important marine layer and elevated duct analyses, a satellite estimate of boundary layer height could be an important input to regional mesoscale models. Insertion of the marine layer depth estimate into the model data assimilation process can improve the analysis and boundary layer forecasts for data-poor marine areas. In addition, future developments may allow model-derived information about advection, upwelling, decoupling, etc., to be used to adjust assumptions in the boundary layer depth algorithm as well.
- Further research on technique performance in shallow STBL cases is needed.
- Develop a robust automation strategy that will allow stand-alone operation.

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